Chapter 4

INFORM Decision Support System (INFORM DSS)

4.1 INTRODUCTION

The INFORM decision support system includes a suite of interlinked models that address reservoir management at hourly, daily, seasonal, and over-year time scales. The 1st year project tasks called for addressing the short- and mid-term time scales, from hours to seasons for two INFORM reservoirs, Folsom and Oroville. Over-year planning and coordination aspects as well as extension for the rest of the INFORM system are scheduled for the 2nd and 3rd project years.

Short- and mid-range reservoir management is addressed through three coupled models: *turbine load dispatching, short range reservoir control* (for a period of one day on hourly time steps), and *mid-range reservoir control* (for a period of several months on daily time steps). As part of this decision support system (DSS), an ensemble *inflow forecasting model* was also developed to test the decision models and to serve as a baseline for the hydrologic forecasting procedures to be implemented later in the project. The DSS is embedded within a user-friendly, *graphical interface* that links the models with the *database* and helps visualize and manage results. A *policy assessment model* has also been developed and is part of the DSS. These DSS components are briefly described next.

4.2 HISTORICAL ANALOG INFLOW FORECASTING MODEL

For tests and baseline comparisons, the DSS includes a Historical Analog (HA) reservoir inflow forecasting model (Yao and Georgakakos, 2001). The model generates an inflow forecast trace ensemble used by the mid range control model. At the final DSS version, the control model will also be able to utilize inflow forecasts from other forecasting schemes being developed at the Hydrologic Research Center. The different forecasting options will be used to assess the value of forecast model type and complexity in reservoir management. A tool to link the forecast results with the reservoir control models was also developed.

HA based inflow forecasting models are developed and calibrated using the historical records for Folsom and Oroville. Retrospective forecasting experiments using the historical records were performed to test and calibrate the models. The reliability, bias, and uncertainty reduction ratios, defined in the above-referenced article, are used as criteria. For selected forecast starting dates and a forecast horizon of 60 days, the results show HA forecast reliability for the two reservoirs is higher than 85%, the uncertainty reduction is about 50% with respect to the historical range, and forecast bias is small. These forecast statistics are reported in Appendix E.

4.3 TURBINE LOAD DISPATCHING

In hydropower plants with many turbines, the turbine load dispatching problem for an individual plant can be expressed as follows: Given a total outflow discharge Q^* and a certain reservoir storage S, determine the discharge q_j through each turbine j and the spillway flow rate s such that $\Sigma q_j + s = Q^*$ and total power P is maximized. Namely, the problem calls for allocating the total discharge among the turbines in a way that maximizes power generation. This mode of operation is also attractive from a water management standpoint because it implies that a given power generation level is achieved at the least possible outflow (water conservation).

In what follows, we present the mathematical formulation of this problem and outline the solution method implemented in the INFORM DSS.

The formulation uses the following notation:

q_j	discharge of turbine j, $j=1, \ldots, n$;
$[q_j^{min}, q_j^{max}]$	discharge operational range for turbine j;
p_j	power load of turbine j;
$[p_j^{min}, p_j^{max}]$	power operational range of turbine j;
Q^*	total discharge target for the entire hydro-plant including spillway outflow, if any;

s	spillway (or other outlet) discharge;
$p_j = g_j(H_n, q_j)$	turbine power generation function relating power generation (p_j) to discharge (q_j) and net hydraulic head (H_n);
$H = f(S)$	reservoir forebay elevation (H) versus storage (S) relationship;
$H_{ls}(Q)$	hydraulic loss function;
$t = r(Q)$	tailwater elevation (t) versus total outflow (Q) curve;
H_n	net hydraulic head.

The objective of the load dispatching problem is to find $\{q_j \text{ and } p_j, j=1,\ldots,n\}$ such that

$$\text{max imize} \quad P = \sum_{j=1}^{n} p_j$$

subject to

$$Q^* = \sum_{j=1}^{n} q_j + s$$

$$H_n = f(S) - r(Q) - H_{ls}(Q),$$

$$p_j = g_j(H_n, q_j),$$

$$p_j^{\min} \le p_j \le p_j^{\max} \quad \text{or} \quad p_j = 0,$$

$$q_j^{\min} \le q_j \le q_j^{\max} \quad \text{or} \quad q_j = 0.$$

An efficient way to handle the various non-linearities and discontinuities of the above-stated problem is to reformulate it in multistage form and solve it via dynamic programming. The multistage formulation is as follows:

$$\text{max imize} \quad J = \sum_{j=1}^{n} p_j(q_j, H_n)$$

subject to

$$X_{j+1} = X_j + q_j, \qquad j = 1,\ldots,n,$$
$$X_1 = 0, \quad X_{n+1} = Q^*$$

$$H_n = f(S) - r(Q^*) - H_{ls}(Q^*),$$

$$p_j^{\min} \le p_j \le p_j^{\max} \quad \text{or} \quad p_j = 0,$$

$$q_j^{\min} \le q_j \le q_j^{\max} \quad \text{or} \quad q_j = 0.$$

Clearly, if the discharge target Q^* is higher than Σq_j^{max}, the problem is trivial and the optimal solution would be to load the turbines at full capacity and pass the excess flow through the spillway or some other outlet facility.

In the previous formulation, the individual turbine discharges (q_j) constitute the control variables and the cumulative discharges (X_j) constitute the state variables. Each stage j represents a different turbine, and the performance index maximizes the total plant power. This problem is in a typical, one-dimensional, dynamic programming form, and can be solved by the traditional backward DP procedure.

An equivalent formulation that also maximizes plant operational efficiency would be to minimize the total plant discharge Q for a given plant power generation P^*. This problem can also be formulated in the same way and solved using dynamic programming.

The load dispatching problem can be solved for various combinations of plant discharge (Q) and reservoir level (H) to define the best efficiency plant power function $P(Q,H)$. This function determines the maximum possible power that can be produced by outflow Q and head H and is used by the short range reservoir control model to represent the power generation function in the reservoir management process. The computations to obtain $P(Q,H)$ are performed only once in an off-line mode. Updating of $P(Q,H)$ is necessary only if turbine characteristics change.

Some results from the turbine load dispatching model for Folsom and Oroville are included in Appendix F. Specifically, the appendix includes the *individual* turbine characteristic curves (power generation versus discharge versus hydraulic head) and the *plant* best efficiency generation functions.

4.4 SHORT RANGE RESERVOIR CONTROL

The purpose of this model is to find the most suitable hourly release schedule within a particular day. The short range model uses the power functions generated by the turbine load dispatching model for each power plant, and must satisfy the daily release target decided by the mid range control model (discussed next). The short range model incorporates all release requirements (pertaining to water supply, flood control, environmental protection, etc.) as well as all power requirements such as dependable capacity commitments. In addition to generating optimal schedules, the model is used in an off-line mode to generate the relationship between daily release, reservoir level, and energy generation to be used by the mid range model.

Denoting R the total daily release volume specified by the mid range control model (upper control level), the objective of the short range model is to determine the hourly discharges *{u(t), t=0, …, 23}* that

$$\text{minimize} \quad J_S[R, H(s(0))] = \sum_{t=0}^{23} F[u(t)] - P[u(t), H(s(t))]$$

subject to

$$s(t+1) = s(t) - u(t) + w(t) - L(t), \quad t = 0, \ldots, 23, \quad s(0) = \text{known},$$

$$R = \sum_{t=0}^{23} u(t)$$

$$u(t) - \Delta u^{\min} \le u(t+1) \le u(t) + \Delta u^{\max}, \quad t = 0, \ldots, 23$$

$$P^{\min}(t) \le P[u(t), H(s(t))] \le P^{\max}(t), \quad t = 0, \ldots, 23$$

$$u^{\min}(t) \le u(t) \le u^{\max}(t), \quad t = 0, \ldots, 23$$

$$s^{\min}(t) \le s(t) \le s^{\max}(t), \quad t = 0, \ldots, 24$$

where t is the time index (in hours); $F[u(t)]$ is the flood damage or cost associated with hourly discharge $u(t)$ including both turbine and spillway outflow; $P[u(t), H(s(t))]$ is the best efficiency plant power function discussed earlier; $H(s(t))$ is the elevation versus storage relationship; $s(t)$ is reservoir storage at the beginning of hour t; $w(t)$ is the inflow (characterized by ensemble forecasts); $L(t)$ is reservoir loss or gain due to water diversions and surface precipitation and evaporation if the latter are significant; P^{min}/P^{max} are power generation constraints; u^{min}/u^{max} are hourly release constraints reflecting low flow, flood control, ecological and other operational requirements; s^{min}/s^{max} are storage constraints; and Δu^{min} and Δu^{max} are operational limits on release decreases and increases from hour to hour.

The previous formulation accounts for different reservoir management objectives through various means. These are discussed in the following comments:

1. The objective function (or performance index) J aims to minimize flood damage and maximize energy generation. Although both terms are present in J, they are usually active during different hydrologic events. Specifically, during low, normal or moderate flows, flooding is not a concern, and the model aims to maximize energy generation (or, equivalently, minimize the negative of $P[\;]$). During such times, low flow, water supply, and other operational requirements (such as dependable capacity constraints) are enforced through the release and power constraints (u^{min}/u^{max} , $\Delta u^{min}/\Delta u^{max}$ *, and* P^{min}/P^{max}). On the other hand, during high floods when significantly higher volumes R must be released, all available hydro turbines run at full gate, and the model is concerned with regulating spillway outflows to mitigate flood damage ($F[\;]$).

2. If the inflow forecast over the next 24 hours is probabilistic, the storage constraints in the above formulation must also be converted in a probabilistic form, reflecting the requirement that the storage bounds s^{min}/s^{max} should not be exceeded by more than a certain tolerance level. Furthermore, in this case, the performance index aims to optimize a statistic of J such as the mean value or a certain percentile of its distribution. However, inflow forecast uncertainty over 24 hours may not translate to considerable uncertainty of reservoir storage, and the previous probabilistic considerations may not be necessary.

3. The above-formulated problem is solved by the Extended Linear Quadratic Gaussian (ELQG) control method (Georgakakos and associates references). However, in cases where daily inflow and outflow is a small fraction of reservoir storage, the problem can be considerably simplified assuming that reservoir level remains constant. This problem does not include the storage dynamical equation and associated constraints (s^{min}/s^{max}) and is solved via a one dimensional dynamic programming scheme.

4. Repeated solution of the short range problem for various combinations of initial reservoir levels $H(s(0))$ and (R-I) yields the daily energy generation function $E[H(s(0), R-I]$, the daily flood damage function $F_l[H(s(0)), R-I]$, and the daily spillage function $S_p[H(s(0)), R-I]$, where (R-I) is the daily release minus the daily inflow. These functions are computed once, in an offline mode, and are used by the mid range control model to represent the benefits and costs associated with particular combinations of reservoir levels, daily releases, and inflow forecasts. If the daily inflow is not appreciable relative to reservoir storage and release, the previous functions are derived in terms of the daily release R, not the difference R-I.

Results from the short range control model for Folsom and Oroville are included in Appendix G. More specifically, the Appendix includes the daily energy generation curves and example runs of 24-hour discharge and energy generation sequences.

4.5 MID RANGE RESERVOIR CONTROL

The mid range control model has a time resolution of one day and a time horizon of several months. The link with the short range control model are the daily energy generation, flood damage, and spillage functions, which ensure that the benefits and consequences associated with daily decisions are realizable in an hourly sense. The mid range model also uses the seasonal forecasts provided by the hydrologic forecasting schemes. The purpose of the model is to (1) assess the relevant operational tradeoffs and (2) determine the reservoir releases associated with the tradeoff regions that might interest the management authorities.

The mathematical formulation of the mid range control problem is similar to that of the short range model, except that it applies to daily quantities and has a control horizon that extends over several months. The objective is to determine the daily release sequences $\{u(t), t=0, \ldots, N-1\}$ that

$$\min imize \quad J_M[H(s(0))] = \{\sum_{t=0}^{N-1} F_l[H(s(t), u(t) - w(t)] - E[H(s(t)), u(t) - w(t)]$$
$$+ S_p[H(s(t)), u(t) - w(t)] + c(t)[s(t) - s^{max}(t)]^2\} + c(N)[s(N) - s^{max}(N)]^2$$

subject to

$$s(t+1) = s(t) - u(t) + w(t) - L(t), \quad t = 0, \ldots, N-1, \quad s(0) = \text{known},$$

$$E^{min}(t) \le E[H(s(t)), u(t) - w(t)] \le E^{max}(t), \quad t = 0, \ldots, N-1$$

$$u^{min}(t) \le u(t) \le u^{max}(t), \quad t = 0, \ldots, N-1$$

$$s^{min}(t) \le s(t) \le s^{max}(t), \quad t = 0, \ldots, N$$

where t is the time index (in days); N is the length of the control (and forecast) horizon; $F_l[\ ]$ is the daily flood damage or cost function associated with initial reservoir level $H(s(t))$, daily release $u(t)$, and inflow forecast $w(t)$; $E[\ ]$ is the daily energy generation function; $S_p[\ ]$ is the daily spillage function; $s(t)$ is reservoir storage at the beginning of day t; $L(t)$ is reservoir loss or gain due to water diversions and surface precipitation and evaporation if the latter are significant; E^{min}/E^{max} are energy generation requirements based on energy contracts; u^{min}/u^{max} are daily release constraints reflecting low flow, flood control, ecological and other operational requirements; s^{min}/s^{max} are storage constraints reflecting flood control and recreational requirements, and $\{c(t), t=0,1,\ldots,N\}$ are coefficients penalizing storage deviations away from its maximum levels $s^{max}(t)$.

The following comments clarify various aspects of the mid range control model formulation.

1. The daily inflow process $\{w(t), t=0, 1, \ldots, N-1\}$ is characterized by forecast ensembles and is thus probabilistic. This inflow characterization is necessary in the mid range model in light of the significant magnitude and uncertainty associated with seasonal inflows. In view of this, the performance index is a random variable, and the objective of the optimization is to minimize its mean or some other percentile. Furthermore, the storage constraints are understood in a probabilistic form,

$$\Pr ob[s^{min}(t) \le s(t)] \ge r^{min}(t), \quad t = 0, \ldots, N,$$

$$\mathrm{Prob}[s(t) \le s^{max}(t)] \ge r^{max}(t), \quad t = 0, \ldots, N,$$

where r^{min} *and* r^{max} are user defined probabilistic levels for keeping the reservoir storage respectively higher and lower than s^{min} *and* s^{max} at prescribed reliabilities.

2. The mid range objective function aims to minimize flood damage and spillage (i.e., spillway releases in excess of turbine capacity), maximize energy generation, and maintain reservoir levels as high as possible while meeting water supply and environmental flow requirements. Clearly, these objectives cannot be met at the highest possible level all at the same time. For this reason, the model is intended first to assess the tradeoffs among the various water uses. Tradeoffs are important information that management authorities can use to select management options in a dynamic fashion. For example, in any given season, a key decision is the portion of reservoir storage that should be reserved for flood control versus energy generation and other purposes. Clearly, more flood control storage would reduce the risk of flood damage. However, it would also draw reservoir levels down and could potentially compromise energy generation and other water uses (e.g., water supply and low flow augmentation) in the ensuing dry season. On the other hand, if the inflow forecast reliably indicates a drier than normal climate, the risks of reducing flood control storage would be small, and the impact to the other water uses less significant. Similar considerations apply to generating more energy versus keeping reservoir levels higher for use in future seasons. Thus, deriving and studying tradeoffs provides an insightful appreciation of the inter-relations among water uses and establishes a holistic perspective of water management.

In the INFORM DSS, tradeoffs are quantified by gradually increasing the reliability parameters and the coefficients *c(t)*. The relationships of various quantities (e.g., flood risk, energy generation, terminals storage, risk of not meeting water supply and low flow requirements, etc.) are then examined and compared. After reviewing this information, the management authorities would decide on an acceptable compromise between benefits and risks. Once this decision is made, the INFORM DSS determines the associated release and storage sequences and is ready to activate the short range control model to refine the daily release volumes into consistent hourly decisions. This process is intended to be sequential and be reevaluated adaptively as time progresses and as more accurate information is collected on the state of the system, the hydrology, and the demands.

3. The above-stated problem is solved by the extended linear quadratic Gaussian control method developed by A. Georgakakos and associates (see attached references), a method suitable for multidimensional and uncertain reservoir systems. Although dynamic programming could also have been used to solve the daily control problem for each reservoir, ELQG is used in anticipation of the basin-wide reservoir coordination that will be required later in the project. The method has the ability to explicitly incorporate all the information contained within the hydrologic forecast ensembles.

Results from the mid range control model for Folsom and Oroville are included in Appendix H. The results correspond to an example model run with 90-day forecast and control horizons, beginning on January 1, 1965. The inflow forecasts are generated by the historical analog model, and the graphs show the reservoir elevation, inflow forecast, release, and energy generation sequences. The graphs indicate that the model manages to keep reservoir levels near the top of the conservation storage with a reliability of 90% (pre-specified).

4.6 POLICY AND SCENARIO ASSESSMENT MODEL

The purpose of the policy and scenario assessment model is to develop a quantitative and consistent procedure to assess the benefits and risks associated with different reservoir regulation policies, forecasting schemes, and water use stresses. The model incorporates the models described above and operates in a sequential fashion that replicates the system management in real time.

Specifically, the process is depicted in the following figure and consists of the sequential, day by day, application of the mid range control model over a user-defined time horizon linked to a daily simulation module recording the system response.

More specifically, the assessment process begins by defining the scenario and policy to be analyzed. The scenario and policy definition involves selecting a particular combination of the following attributes:

- Inflow time series over which to assess policy: Historical or generated data; time horizon (i.e., beginning and ending dates);
- Water use levels: water supply and low flow requirements, energy and dependable capacity contracts, flood control thresholds, reliability parameters;
- System configuration: Reservoirs and hydro plants on-line; unit maintenance schedules;
- Inflow forecasting scheme: deterministic or ensemble type, hydrology based, hydrology and climate based;
- Release policy type: Operational practices, adaptive dynamic.

Clearly, the number of potential scenarios is very large, adding to the versatility and value of this DSS component. For a certain scenario, the assessment process is as follows: First, future inflows are forecasted based on the scheme selected. Next, the mid range model is activated to develop release and generation schedules for the system reservoirs and hydropower plants. The releases for the first day of the control horizon and the daily inflows (unknown up to this time) are applied, and the system response (reservoir levels, releases, spillage, water supply deficits, energy generation and shortages, and flood damage if any) is simulated and recorded. This process is repeated for the next day until the end of the assessment horizon. At the conclusion of the assessment process, several criteria are used to measure system performance, including statistics of water supply deficits, energy generation, flood damage, violation of low flow requirements, reservoir drawdowns, and other quantities relevant to reservoir management. Model development has been completed for both Folsom and Oroville. Representative results from this model are shown in Appendix I.

Specifically, assessment results are first shown for a 6-month period from January 1, 1984 through January 31, 1984. The mid range model is run adaptively on a daily basis using a 90 day inflow forecast from the historical analog model. The management purpose is to avoid flooding, pass all of the release through the plant turbines and avoid spillage, meet the water supply requirements, and maintain reservoir storages as high as possible. The graphs show that the model accomplishes this objective for both reservoirs.

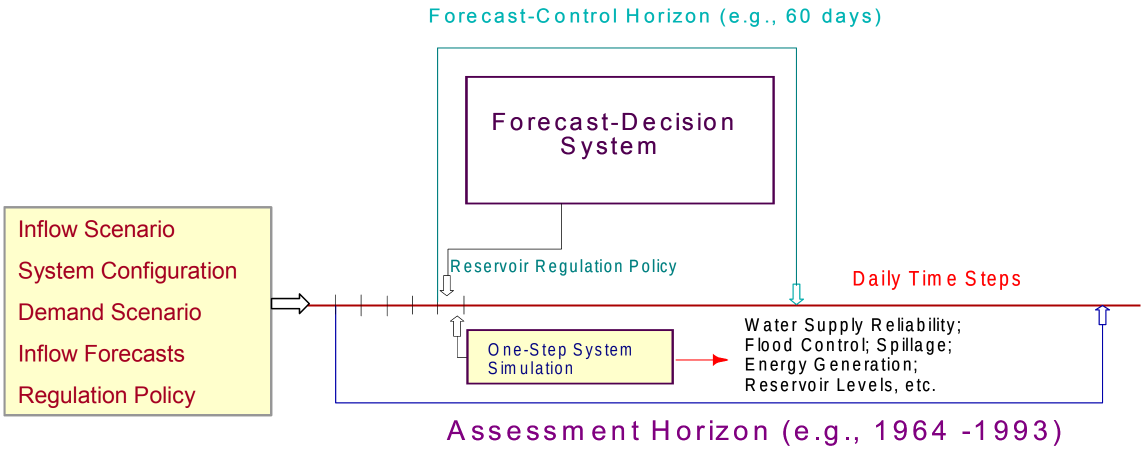

Figure 4.4.1: Policy and Scenario Assessment Framework

The second assessment run aims to compare the system response under simple release rules (rule curves) and deterministic forecasts versus dynamic release rules and ensemble type forecasts. The results tabulated in the appendix show that static regulation rules cannot take full advantage of inflow forecasts, leading to less energy generation and inability to balance reservoir management during wet and dry climatic periods. Furthermore, ignoring forecast uncertainty in the management process leads to increased risk of flooding and eventually higher flood damages.

4.7 DSS DATABASE, UTILITY TOOLS, AND INTERFACE

The management models of the INFORM DSS are framed within a graphical interface that provides access to data, activates model runs, and visualizes/manages model results.

Database: The DSS database uses the MS ACCESS engine. All system data and model inputs and outputs are organized in MS ACCESS relational tables. The data in the database are accessible from the DSS interface and can be easily visualized and updated through EXCEL and graphical menu screens. The interface is written in MS Visual Basic. Interface implementation for the database has been completed, and the available data have been incorporated into the database. A listing of the data is provided in Appendix J.

Data Processing and Utility Tools: Use of the original data by the various DSS models requires processing. For example, the reservoir control models require analytic forms of the reservoir elevation-storage and elevation surface curves. Such curves can be derived via regression analysis. To automate this process, a regression utility tool has been developed. This tool allows the user to generate the analytic data relationships interactively. Other utility tools are also developed to derive optimal power plant functions and daily energy functions.

Interface Functions: As explained earlier, the DSS includes a suite of reservoir management models to support decisions pertinent to long range planning as well as short range scheduling. The control models have a hierarchical structure according to their time resolution. In a typical run, the interface enables the user to run the forecasting model first, followed by the seasonal control model, the hourly control model, and the turbine load dispatching model. In this execution order, the results of the upper level models are automatically passed onto the lower level models. In addition, the DSS interface also allows the user to run all applications independently. The user can start with any of the models without previously running any of the upper level models. In this case, however, one would have to prepare the required input data externally. The DSS interface also provides Excel templates to assist the user prepare input data externally for all models.

These DSS features have been demonstrated at the 2nd oversight project meeting and will be demonstrated at a forthcoming technical workshop.

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